Screening Level Assessment of Risks Due to Dioxin Emissions from Burning Oil from the BP Deep Water Horizon Gulf of Mexico Spill

(slides prepared at ARL Jan 2011, based on earlier ARL materials prepared Oct 2010)

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As one of the methods to respond to the oil spill, 410 separate *in-situ* burns were carried out between April 28 and July 19, burning an estimated 222,000-313,000 barrels of oil (~5% of the total amount of leaked oil)

Dioxin Risk?

- Polychlorinated dibenzo-p-dioxins and furans (referred to as PCDD/F or “dioxin”) are formed in trace amounts during combustion
- The presence of chlorine in the combustion environment can enhance PCDD/F formation
- The marine environment has relatively high levels of chlorine, and so there was concern that the oil burning activities might be releasing harmful levels of dioxin
- There are 209 different PCDD/F congeners; 2,3,7,8-TCDD is the most toxic and is one of the most potent carcinogenic compounds ever discovered

A joint "screening level" project was undertaken by the EPA and NOAA to assess the potential dioxin risk from the oil burning activities

Overall Outline of Project

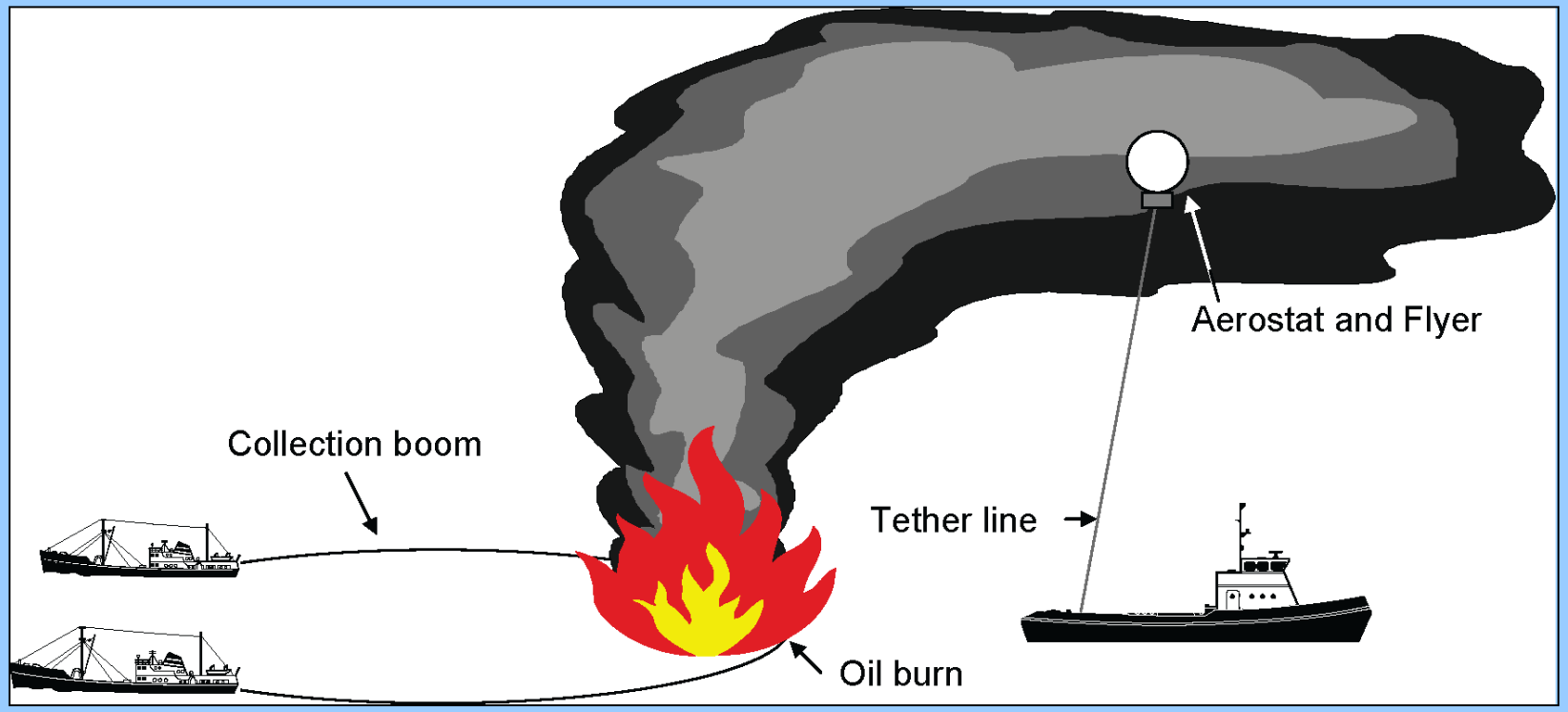
- Overall goal was to estimate inhalation risk to workers and residents, as well as risk from consumption of dioxin-contaminated seafood
- This was a screening level analysis -- if the risks appeared high enough, a more detailed assessment would be carried out
- Dioxin was measured in DWH-oil-burning plumes by EPA to estimate emissions factor
- Relevant burn-by-burn data and meteorological data were assembled for use as model inputs
- Atmospheric dispersion models used to estimate air concentrations of dioxin downwind of the burns; inhalation exposure and cancer risks from this exposure were based on these estimates.
- Atmospheric deposition was estimated by dispersion models and utilized in a food chain model to estimate dioxin concentrations in fish; cancer risk from fish consumption based on these estimates.

NOAA ARL's Contributions

- Carrying out analysis on burn-by-burn data to create a dataset suitable for model input. (ARL appreciates the assistance of NOS/OR&R in relaying these data.)
- Assembling/archiving gridded meteorological data for use in ARL's atmospheric modeling; extracting data from these archives to support EPA's near-field modeling work
- NOAA ARL was asked by U.S. EPA to begin modeling atmospheric fate and transport of emitted dioxin on June 18, 2010 to inform assessment of risks to the general population. Numerous model runs were carried out over the next four months as additional data became available.
- This ARL atmospheric modeling analyzed the regional fate and transport of emitted dioxin, on a congener-specific and burn-by-burn basis, using a specially configured version of the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model designed to simulate atmospheric PCDD/F.
- Based on this modeling, ARL provided screening-level values of atmospheric deposition and on-shore concentrations for use in the EPA's risk assessment

EPA measured the dioxin emissions from several plumes to estimate an emissions factor for the oil-burning activities

Aurell and Gullett (2010). Aerostat Sampling of PCDD/PCDF Emissions from the Gulf Oil Spill In Situ Burns. *Environ. Sci. Technol.* **44**, 9431–9437

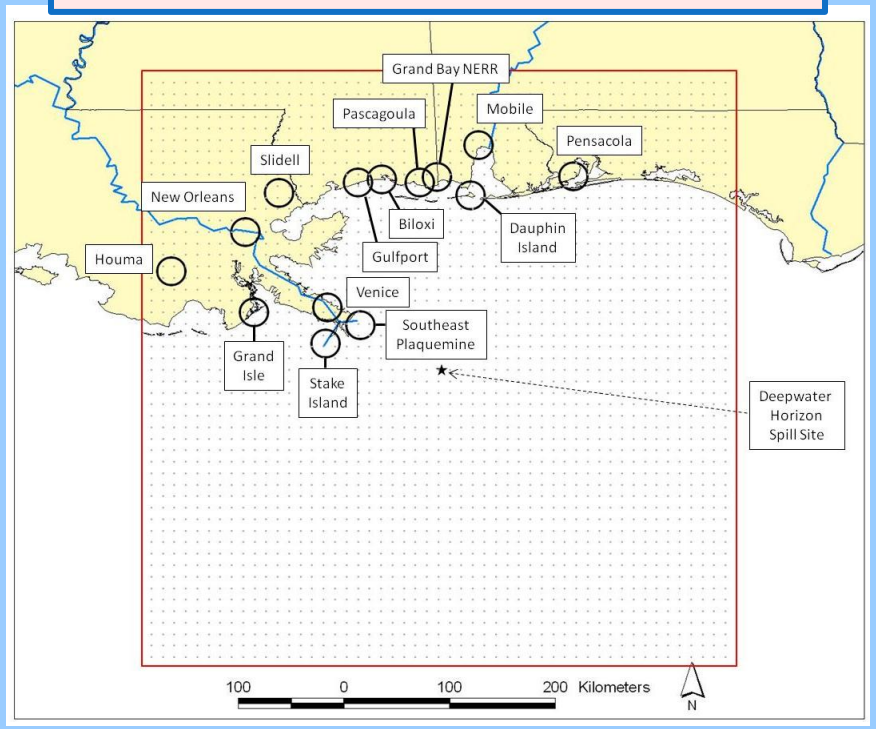


Schematic illustration of the in situ burn operations and plume sampling.
(Figure 1 from Aurell and Gullett, 2010)

The NOAA HYSPLIT model was used to simulate the atmospheric fate and transport of dioxin emitted from the burning activities

- HYSPLIT modified for PCDD/F: Cohen, Draxler, Artz et al. *Environ. Sci. Technol*. **2002,** 36, 4831-4845.
- Each of the 410 surface burn events modeled.
- Simulation from 4/28/2010 (date of first burn) to 7/22/2010 (3 days past last burn 7/19/2010).
- Hourly met data from NOAA NCEP NAM weather model.
- Met data horizontal resolution: 12 km.
- Met data vertical resolution: 18 of 39 levels <= 1500m.
- Overall model domain was 10^o x 10^o centered at spill.
- Results tabulated on 5^o x 5^o grid; resolution of 10 km.
- Time series data tabulated at 14 illustrative sites.
- Burn-specific buoyancy-driven plume rise estimated.
- Simulated each 2,3,7,8-substituted PCDD/F congener.
- Individual congener simulations added together using the congener-specific emissions factors and congener-specific toxic-equivalence factors, to create results as TEQ.

Modeling results tabulated at 10km resolution on a 5^o x 5^o grid and at 14 illustrative sites

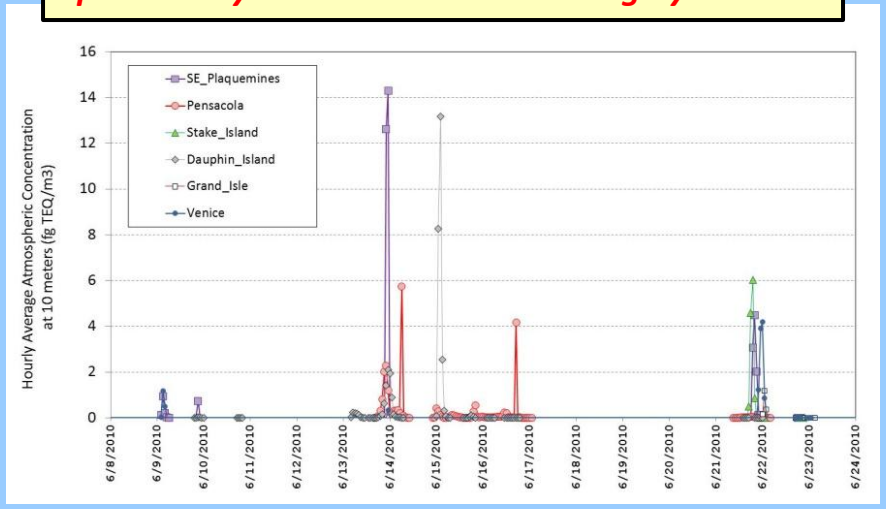


Simulation results grid and locations of 14 illustrative sites chosen for more detailed accounting

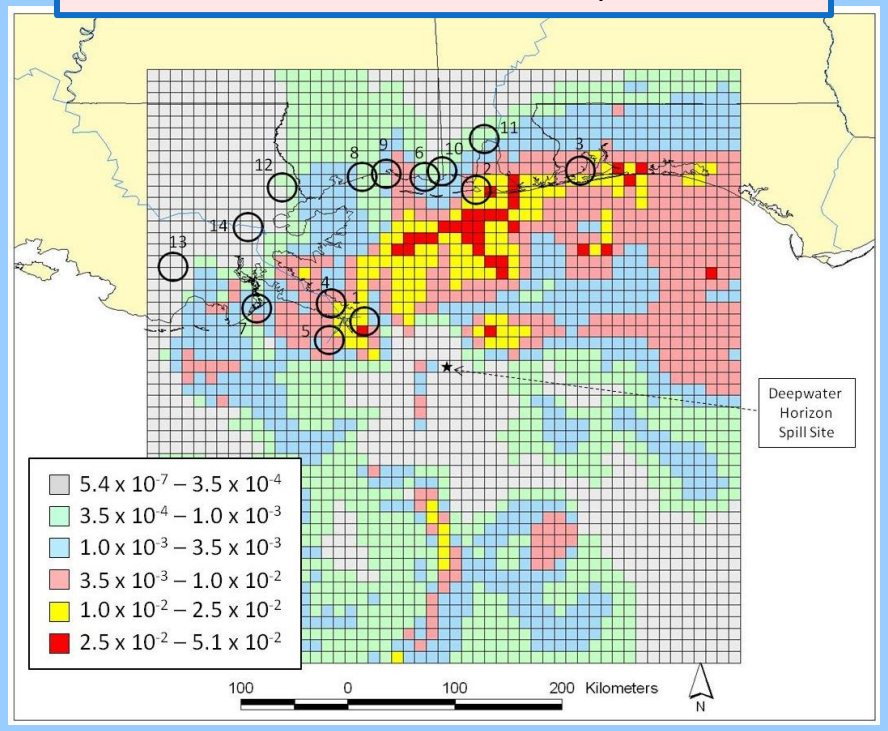
Ground-Level Atmospheric Concentrations

These data were used by EPA used to estimate on-shore inhalation exposure and the cancer risk associated with that exposure

Ground-level dioxin concentrations were very episodic, due to the fact that burns occurred sporadically and the weather was highly variable



Time series of modeled hourly average PCDD/F concentrations (at 10 meter elevation) for a portion of the burning period (June 8-24) at several illustrative locations in the Gulf of Mexico region resulting from estimated dioxin emissions from reported burn events.



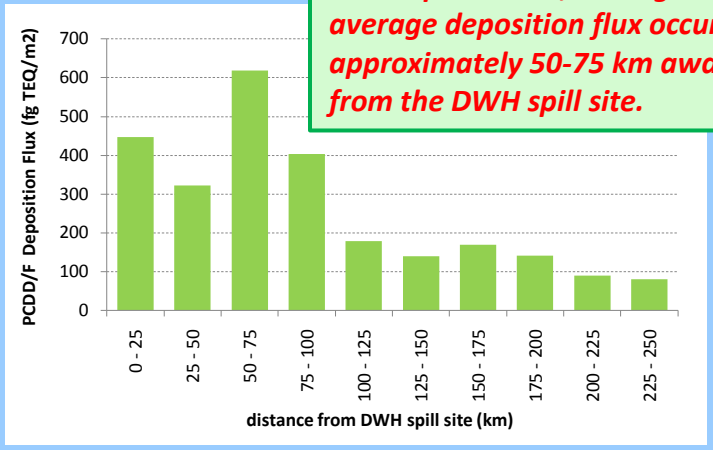
Average modeled ground-level PCDD/F concentrations (fg TEQ/m3) over the entire modeling period April 28 – July 22, 2010.

Illustrative locations shown, numbered in descending order from highest to lowest average concentration (fg TEQ/m3):

1 – S.E. Plaquemines (0.019)
2 – Dauphin Island (0.016)
3 – Pensacola (0.012)
4 – Venice (0.0072)
5 – Stake Island (0.0069)
6 – Pascagoula (0.0011)
7 – Grand Isle (0.0010)
8 – Gulfport (0.00095)
9 – Biloxi (0.00066)
10 – Grand Bay NERR (0.00065)
11 – Mobile (0.00052)
12 – Slidell (0.00025)
13 – Houma (0.00018)
14 – New Orleans (0.00008)

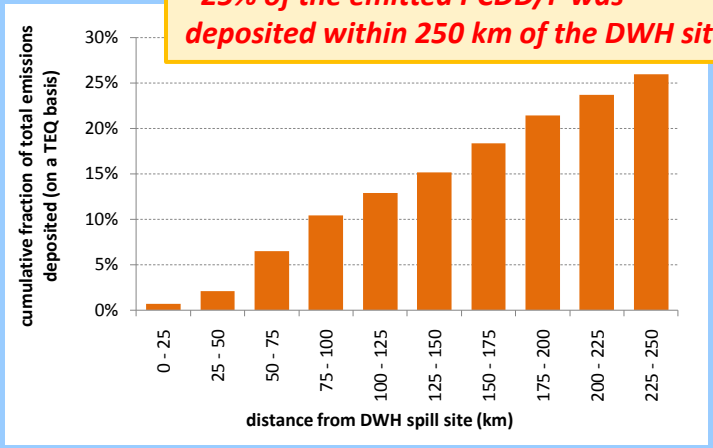
Atmospheric Deposition

Due to plume rise, the highest average deposition flux occurred approximately 50-75 km away from the DWH spill site.



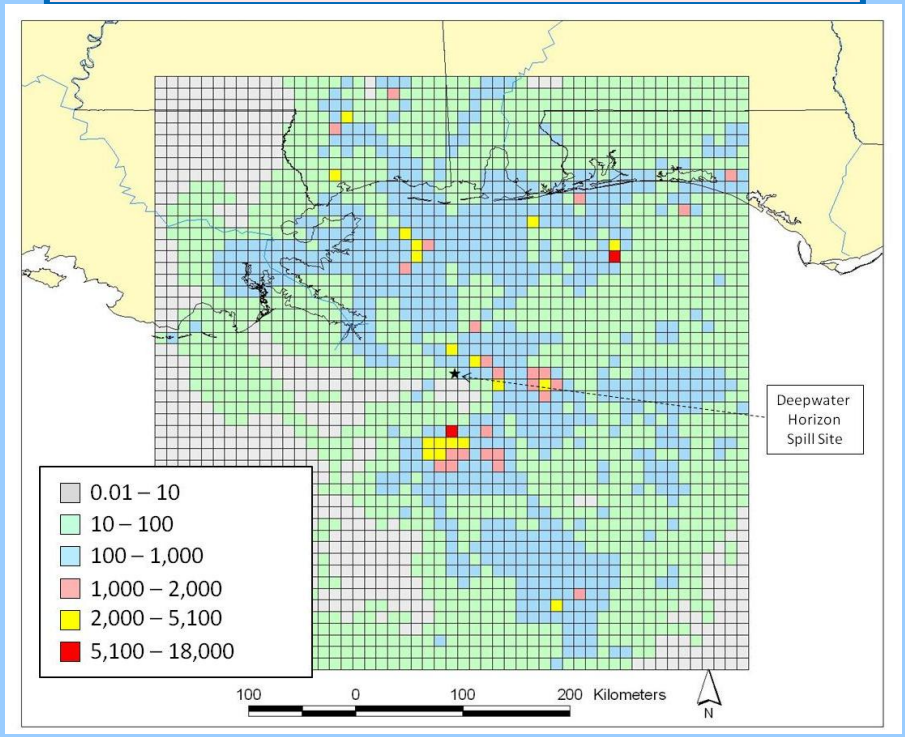
Average Dioxin Deposition Flux (fg TEQ/m2) at Different Distances Away from the DWH Spill Site

~25% of the emitted PCDD/F was deposited within 250 km of the DWH site



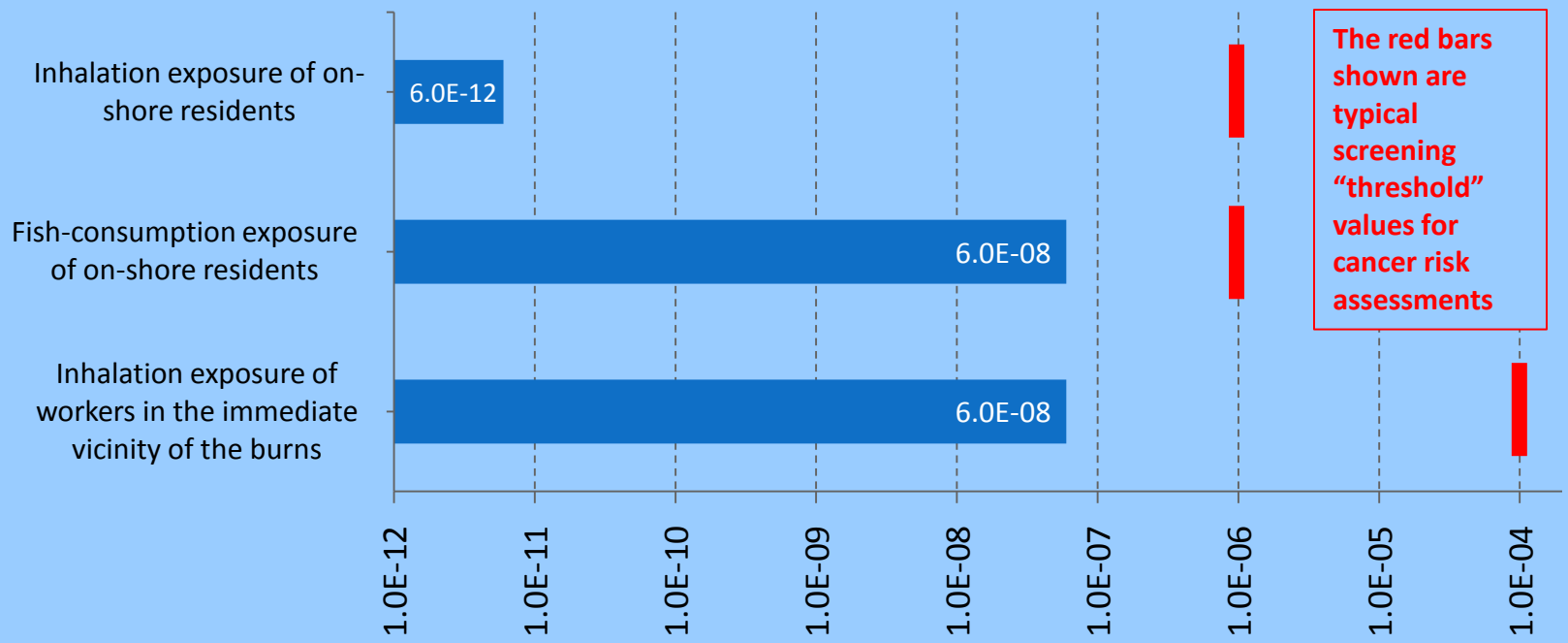
Cumulative Fraction of Dioxin Emissions Deposited at Different Distances Away from the DWH Spill Site

EPA used these data as input to a food chain model to estimate dioxin concentrations in fish and risks to the general population from eating those fish



Total PCDD/F deposition flux (fg TEQ/m2) over the entire modeling period April 28 – July 22, 2010.

Upper-bound lifetime incremental cancer risk



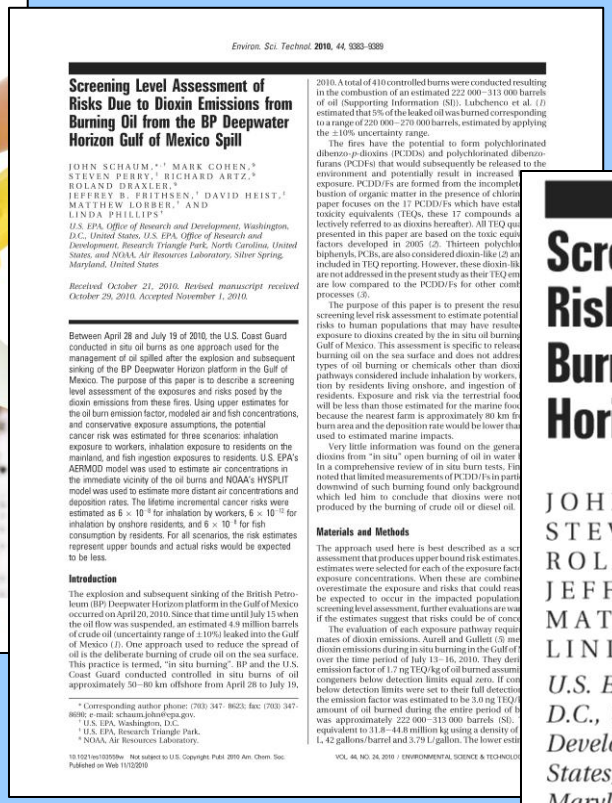
Current Status

- Manuscript underwent internal (EPA and NOAA) and external peer reviews
- Manuscript published: Screening Level Assessment of Risks Due to Dioxin Emissions from Burning Oil from the BP Deepwater Horizon Gulf of Mexico Spill, *Environmental Science and Technology* **2010**, 44, 9383–9389

Issues

- *This risk assessment was for dioxin emissions only. It did not consider other chemicals likely emitted, e.g., PAH's (polycyclic aromatic hydrocarbons).*
- *This risk assessment only considered emissions from in-situ oil burning. It did not consider emissions from other DWH-related oil-burning activities, e.g., on the Q-4000.*
- *There were significant uncertainties in available information about the characteristics (e.g., area of burn, plume rise) of individual burn events. For future incidents, additional information (e.g., photo's of plumes) would improve accuracy of risk assessments*

Publication Detailing Study Results



Environ. Sci. Technol. **2010**, 44, 9383–9389

Screening Level Assessment of Risks Due to Dioxin Emissions from Burning Oil from the BP Deepwater Horizon Gulf of Mexico Spill

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Between April 28 and July 19 of 2010, the U.S. Coast Guard conducted in situ oil burns as one approach used for the management of oil spilled after the explosion and subsequent sinking of the BP Deepwater Horizon platform in the Gulf of Mexico. The purpose of this paper is to describe a screening level assessment of the exposures and risks posed by the dioxin emissions from these fires. Using upper estimates for the oil burn emission factor, modeled air and fish concentrations, and conservative exposure assumptions, the potential cancer risk was estimated for three scenarios: inhalation exposure to workers, inhalation exposure to residents on the mainland, and fish ingestion exposures to residents. U.S. EPA's AERMOD model was used to estimate air concentrations in the immediate vicinity of the oil burns and NOAA's HYSPLIT model was used to estimate more distant air concentrations and deposition rates. The lifetime incremental cancer risks were estimated as 6×10^{-8} for inhalation by workers, 6×10^{-12} for inhalation by onshore residents, and 6×10^{-9} for fish consumption by residents. For all scenarios, the risk estimates represent upper bounds and actual risks would be expected to be less.

Introduction

The explosion and subsequent sinking of the British Petroleum (BP) Deepwater Horizon platform in the Gulf of Mexico occurred on April 20, 2010. Since that time until July 15 when the oil flow was suspended, an estimated 4.9 million barrels of crude oil (uncertainty range of ±10%) leaked into the Gulf of Mexico (*1*). One approach used to reduce the spread of oil is the deliberate burning of crude oil on the sea surface. This practice is termed, "in situ burning". BP and the U.S. Coast Guard conducted controlled in situ burns of oil approximately 50–80 km offshore from April 28 to July 19, 2010. A total of 410 controlled burns were conducted resulting in the combustion of an estimated 222 000–313 000 barrels of oil (Supporting Information (SI)). Lubchenco et al. (*1*) estimated that 5% of the leaked oil was burned corresponding to a range of 220 000–270 000 barrels, estimated by applying the ±10% uncertainty range.

The fires have the potential to form polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) that would subsequently be released to the environment and potentially result in increased exposure. PCDD/Fs are formed from the incomplete combustion of organic matter in the presence of chlorine. This paper focuses on the 17 PCDD/Fs which have established toxicity equivalents (TEQs, these 17 compounds are collectively referred to as dioxins hereafter). All TEQ quantities presented in this paper are based on the toxic equivalency factors developed in 2005 (*2*). Thirteen polychlorinated biphenyls, PCBs, are also considered dioxin-like (*2*) and are included in TEQ reporting. However, these dioxin-like PCBs are not addressed in the present study as their TEQ emissions are low compared to the PCDD/Fs for other combustion processes (*3*).

The purpose of this paper is to present the results of a screening level risk assessment to estimate potential risks to human populations that may have resulted from exposure to dioxins created by the in situ oil burning in the Gulf of Mexico. This assessment is specific to releases from burning oil on the sea surface and does not address other types of oil burning or chemicals other than dioxins. The pathways considered include inhalation by workers, ingestion by residents living onshore, and ingestion of fish by residents. Exposure and risk via the terrestrial food chain will be less than those estimated for the marine food chain because the nearest farm is approximately 80 km from the burn area and the deposition rate would be lower than that used to estimated marine impacts.

Very little information was found on the general topic of dioxins from "in situ" open burning of oil in water. In a comprehensive review of in situ burn tests, Fingas (*4*) noted that limited measurements of PCDD/Fs in particulate downwind of such burning found only background levels which led him to conclude that dioxins were not produced by the burning of crude oil or diesel oil.

Materials and Methods

The approach used here is best described as a screening assessment that produces upper bound risk estimates. Upper estimates were selected for each of the exposure factors (e.g., exposure concentrations. When these are combined, they overestimate the exposure and risks that could reasonably be expected to occur in the impacted population. The screening level assessment, further evaluations are warranted if the estimates suggest that risks could be of concern.

The evaluation of each exposure pathway required estimates of dioxin emissions. Aurell and Gullett (*5*) measured dioxin emissions during in situ burning in the Gulf of Mexico over the time period of July 13–16, 2010. They derived an emission factor of 1.7 ng TEQ/kg of oil burned assuming congeners below detection limits equal zero. If congeners below detection limits were set to their full detection limits, the emission factor was estimated to be 3.0 ng TEQ/kg. The amount of oil burned during the entire period of burning was approximately 222 000–313 000 barrels (SI), which is equivalent to 31.8–44.8 million kg using a density of 0.9 kg/L, 42 gallons/barrel and 3.79 L/gallon. The lower estimate

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Related Publications Regarding Study

Environ. Sci. Technol. **2010**, *44*, 9431–9437

Aerostat Sampling of PCDD/PCDF Emissions from the Gulf Oil Spill In Situ Burns

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Emissions from the in situ burning of oil in the Gulf of Mexico after the catastrophic failure of the Deepwater Horizon drilling platform were sampled for polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDD/PCDF). A battery-operated instrument package was lofted into the plumes of 27 surface oil fires over a period of four days via a tethered aerostat to determine and characterize emissions of PCDD/PCDF. A single composite sample resulted in an emission factor of 2.0 ng toxic equivalency (TEQ) per kg of carbon burned, or 1.7 ng TEQ per kg of oil burned, determined by a carbon balance method. Carbon was measured as CO_2 plus particulate matter, the latter of which has an emission factor of 0.088 kg/kg carbon burned. The average plume concentration approximately 200−300 m from the fire and about 75−200 m above sea level was <0.0002 ng TEQ/m^3.

Introduction

The Deepwater Horizon oil drilling platform located in the Gulf of Mexico, owned and managed by Transocean for British Petroleum (BP), caught fire on April 20, 2010 and sank. Eleven lives were lost and the ensuing oil leak resulted in an environmental disaster for the Gulf region. The U.S. Coast Guard (USCG) and BP undertook operations to collect and burn the surface oil as one means of limiting its environmental impact. Pairs of vessels, typically fishing trawlers, towed a collection boom through surface oil slicks, accumulating oil. Smaller "igniter" boats placed an incendiary starter charge (gelled diesel in a plastic container with foam flotation and a road flare) within the boom's oil pool to promote ignition. Under appropriate conditions of the oil and the sea/wind state, the collected oil would ignite, burning for times varying from minutes to hours. The USCG estimated that between 220,000 and 310,000 barrels of oil were consumed during 411 in situ burns between April 28, 2010 and July 19, 2010 (*1*).

In situ burning of oil spills has the benefit of minimizing contamination of coastal marine environments. Probably the largest detriment is the emissions from the incomplete combustion of the oil, as indicated by the copious volumes of black, particle-laden smoke. Various efforts have been undertaken to quantify the emissions from in situ burns, the most comprehensive at-sea effort being the Newfoundland offshore burn experiments (*2*). Particle and gas concentrations sampled by aircraft-borne instruments were developed into emission factors (*3*) using a carbon balance approach (mass of pollutant per mass of fuel carbon). Other measurements were made using samplers aboard remotely controlled marine vessels and tethered aerostats (*4*).

Emissions of polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDD/PCDF) from the oil burns are of interest due to their health effects (*5*) including immunotoxicity, carcinogenicity, and teratogenicity. The potential for PCDD/PCDF emissions from the Gulf in situ burns exists due to the apparent presence of the prerequisite conditions for formation: incomplete combustion, the presence of trace metals as catalysts, and availability of chloride in the seawater. Few measurements of PCDD/PCDF have been made from oil fires and only one (*2*) to our knowledge from an at-sea burn similar to those of the Gulf in situ burns. Results from two samples at sea level were reported as indistinguishable from background levels, leading to the conclusion that PCDD/PCDF were not formed from oil spill burns (*6, 7*). Similar conclusions were reached during experimental, mesoscale burns (*4*) when ground-based emission samples were compared against upwind sampling. In both of these cases the PCDD/PCDF sampling was done at sea/ground level, apparently outside of the visible plume, so questions remain regarding their ability to resolve whether or not PCDD/PCDF are formed.

To measure the potential emissions of PCDD/PCDF from the Gulf in situ oil burns, an aerostat-lofted instrument package was used to sample the plume emissions to determine PCDD/PCDF concentrations and an emission factor.

Materials and Methods

Aerostat Operations at Sea. A 4.0-m diameter, helium-filled aerostat (Kingfisher model, Aerial Products Inc., FL) was used to loft an instrument package (termed the "Flyer") into oil fire plumes for sample collection. The aerostat/Flyer were launched from the deck of the MV Allison (Aries Corporation), a 67-m long oil platform work boat. The aerostat was secured to an electric winch by a 609-m long, 2.5-mm diameter Spectra tether. Tethered aerostat flight operations were conducted in accordance with regulations for moored aerostats (*8*). Because of increased air traffic in support of oil spill operations, several additional operational requirements were coordinated with the Federal Aviation Administration (FAA) and Incident Command Post (ICP). These requirements included daily altitude restrictions, a dedicated air traffic observer, two-way radio contact on Common Traffic Advisory Frequency, and availability of a signal flare if necessary to visually alert aircraft to our presence. The FAA published a daily Notice to Airmen (NOTAM) advising pilots that tethered aerostat operations were being conducted in the area. The FAA also required notification prior to each flight operations period including precise location in relation to the Deepwater Horizon source, any position changes of more than 1.85 km, and termination of the daily flight operations. As a further precaution, the Aerostat Flyer was equipped with a radio-controlled deflation valve in the unlikely event it became loose from its tether. Filling the aerostat with helium and lofting the Flyer to the sampling

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J. Aurell and B. Gullett (2010). Aerostat Sampling of PCDD/PCDF Emissions from the Gulf Oil Spill In Situ Burns. *Environ. Sci. Technol.* **44**, 9431–9437

Environ. Sci. Technol. **2010**, *44*, 9250–9251

ENVIRONMENTAL Science & Technology Viewpoint

Designing Science in a Crisis: The Deepwater Horizon Oil Spill

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RHONDA SAUNDERS

In a crisis, there is little room for prolonged debate or hesitation. Decisions can yield tremendous consequences and time is of the essence.

The Deepwater Horizon (DWH) oil spill, like many disasters before it, challenged the scientific community to do their best work under dire circumstances. Scientists from more than a dozen federal agencies and the private and academic communities were called to bring the best science, expertise, and assets to bear on an unprecedented situation. As teams worked together to respond to what President Obama called "the worst environmental disaster America has ever faced", scientists were denied the luxury of lengthy deliberation.

In this issue of Environmental Science & Technology, there are two examples of "crisis science" designed and conducted by the U.S. Environmental Protection Agency (EPA) to support the DWH oil spill response (*1, 2*). They represent efforts made in the midst of a disaster to determine whether dioxins formed during controlled surface burns and, if so, what the potential impacts were.

These two papers are just a small piece of a much larger story about designing the best possible science during an environmental emergency.

In a crisis, scientists face a unique set of challenges:

- Realized or potential adverse consequences
- Significant uncertainties and unknowns
- An urgent time frame for decisions and actions

Throughout the DWH spill, there was a direct threat of oil reaching shoreline ecosystems, harming aquatic species, compromising fisheries, and impacting communities. There were also potential indirect concerns associated with response actions like controlled burns and dispersant use. EPA worked with interagency teams to address these immediate threats without losing sight of the secondary, yet equally important, concerns.

The ongoing disaster also presented extraordinary challenges and unknowns. The combination of the spill's depth at sea and distance from shore was unprecedented. The spill's elusive flow rate and unpredictable cessation posed tremendous scientific unknowns. Scientists worked amidst these challenges and under urgent time pressure for three months.

Despite challenges that seemed, at times, insurmountable, EPA worked to uphold its commitment to scientific integrity—because to adequately support decision-making, science has to be strong. To cope with this requirement and produce the best possible work, EPA designed a crisis science framework around three fundamental elements.

The first element involved *tapping into all existing relevant knowledge.* The DWH spill was not the first oil spill, nor even the first spill in the Gulf of Mexico to require a response. Searching for lessons learned from events like the Exxon Valdez and Ixtoc spills was an important first step. Scientists also turned to previously published analyses such as those conducted by the U.S. National Academy of Sciences (*3*) to learn as much as possible from the existing body of response technology literature. EPA gathered information about relevant work within the Agency and engaged academic institutions, especially those along the Gulf coast, to take advantage of ongoing research and avoid duplication of effort.

The second element was *working to understand and meet the specific needs of the crisis response.* There were a myriad of scientifically interesting questions surrounding the DWH oil spill. EPA scientists needed to prioritize only those questions that would directly inform the emergency response. This is why EPA, with its partners, implemented air, water, and sediment monitoring regimes. This is also why interagency scientists conducted daily monitoring of dissolved oxygen levels, organism (rotifer) mortality, and particle size. To understand the impact and effectiveness of dispersant use, EPA conducted comparative toxicity tests (*4*) that informed actions and decisions. The testing for dioxin formation described in this journal was undertaken on the

P. Anastas, C. Sonich-Mullin, and B. Fried (2010). Designing Science in a Crisis: The Deepwater Horizon Oil Spill. *Environ. Sci. Technol.* **44**, 9250-51

additional information from the modeling analysis included in the Supplementary Information published along with the ES&T paper

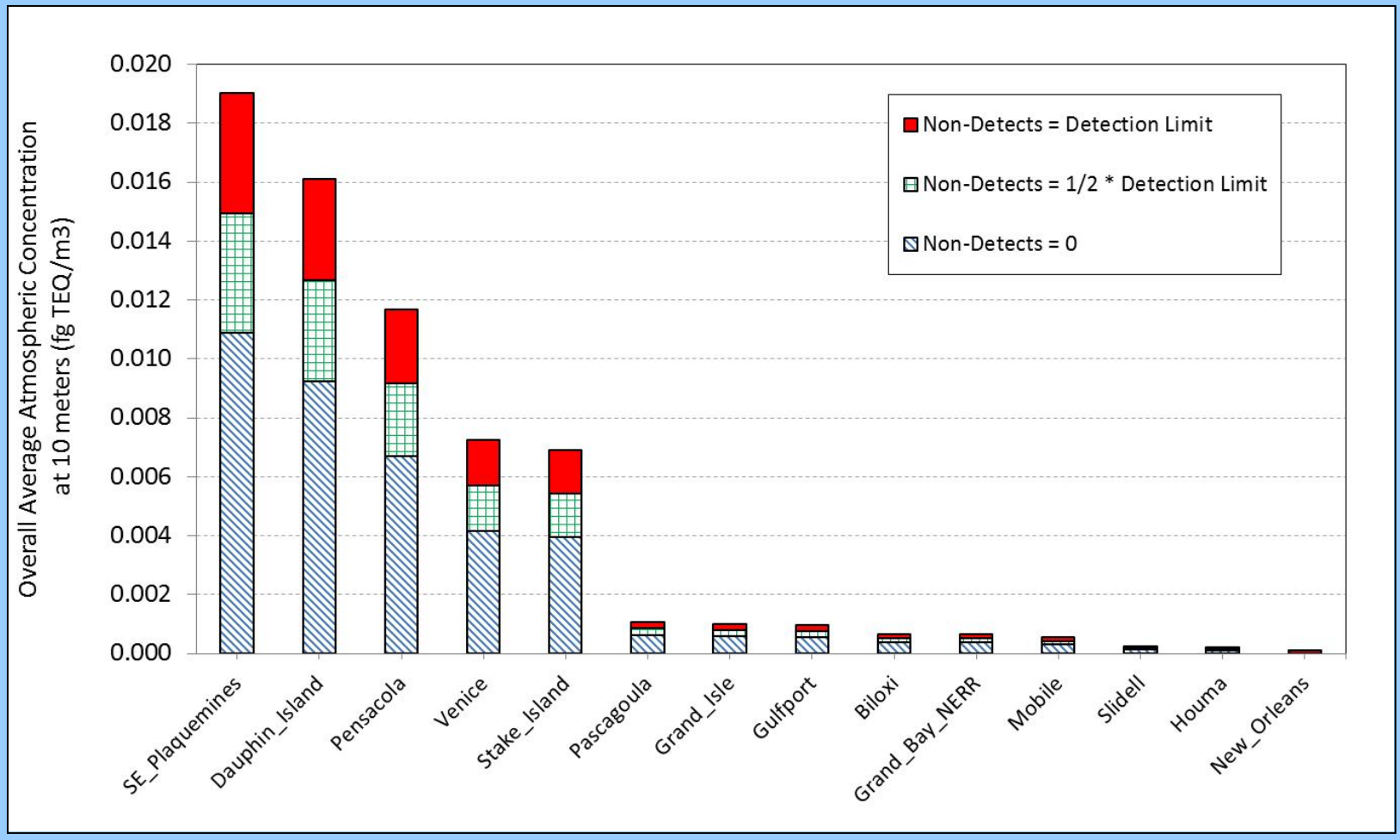

Figure S-3. Average modeled concentrations at 10 meter elevation for the entire modeling period at 14 selected locations in the Gulf of Mexico region.

Note that the maximum values (representing emissions estimated assuming non-detected congeners were present at the detection limit) are the data tabulated in the caption to the map on slide #5 above.

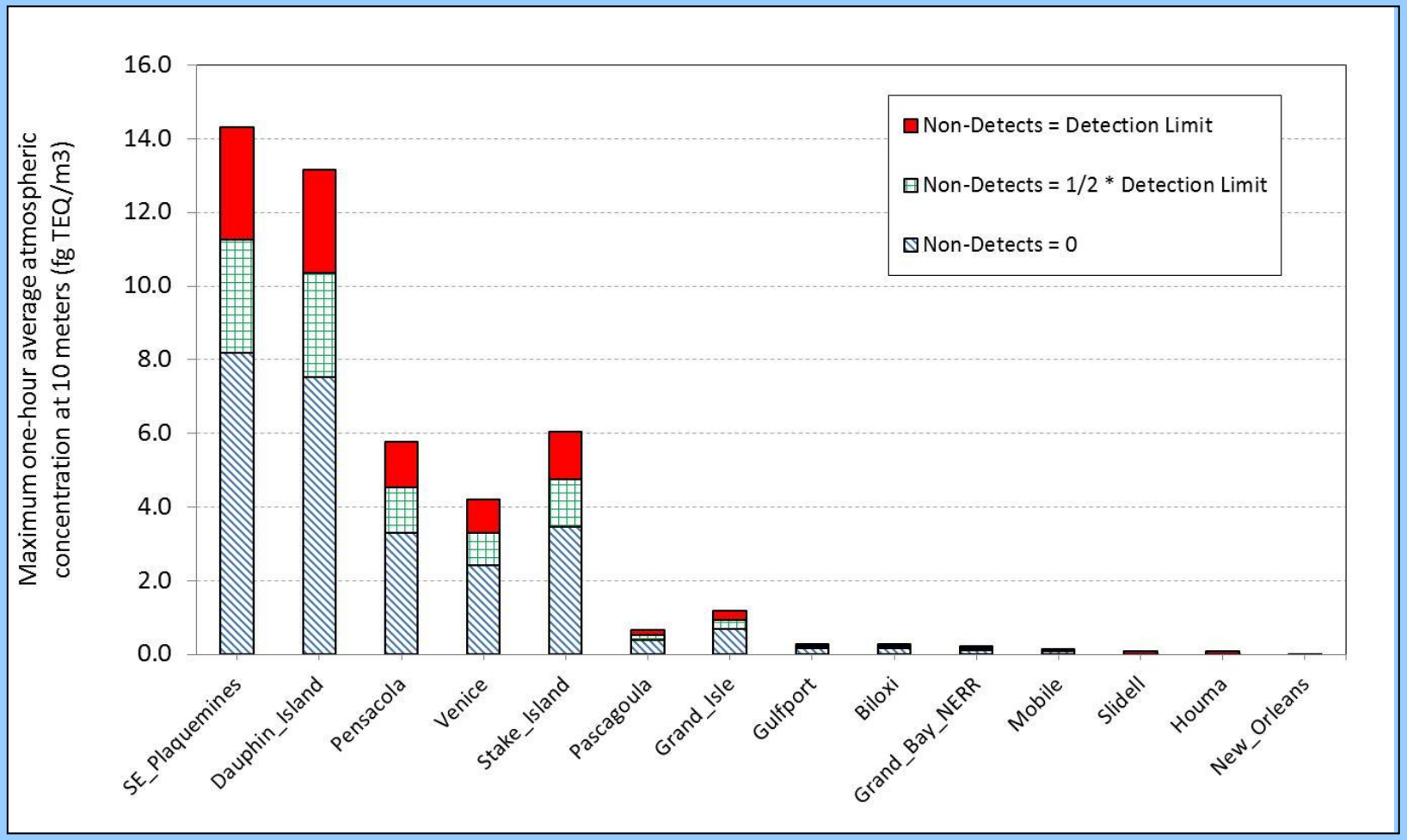

Figure S-4. Maximum modeled one-hour average concentrations at 10 meter elevation for the entire modeling period at 14 selected locations in the Gulf of Mexico region.

- An earlier slide (#5 above) showed the average modeled ground level concentration over the entire modeling period April 28 -- July 22, 2010 for each grid square.
- This figure shows the *maximum 24-hour-average*, modeled ground-level (10 m) concentrations for each grid square over the same period.
- The highest 24-hr-average modeled shoreline (or inland) concentrations was 0.92 fg TEQ/m^3, and this occurred at the grid square with centroid latitude /longitude of 30.2367 / -87.7872 (near the Bon Secour National Wildlife Refuge).

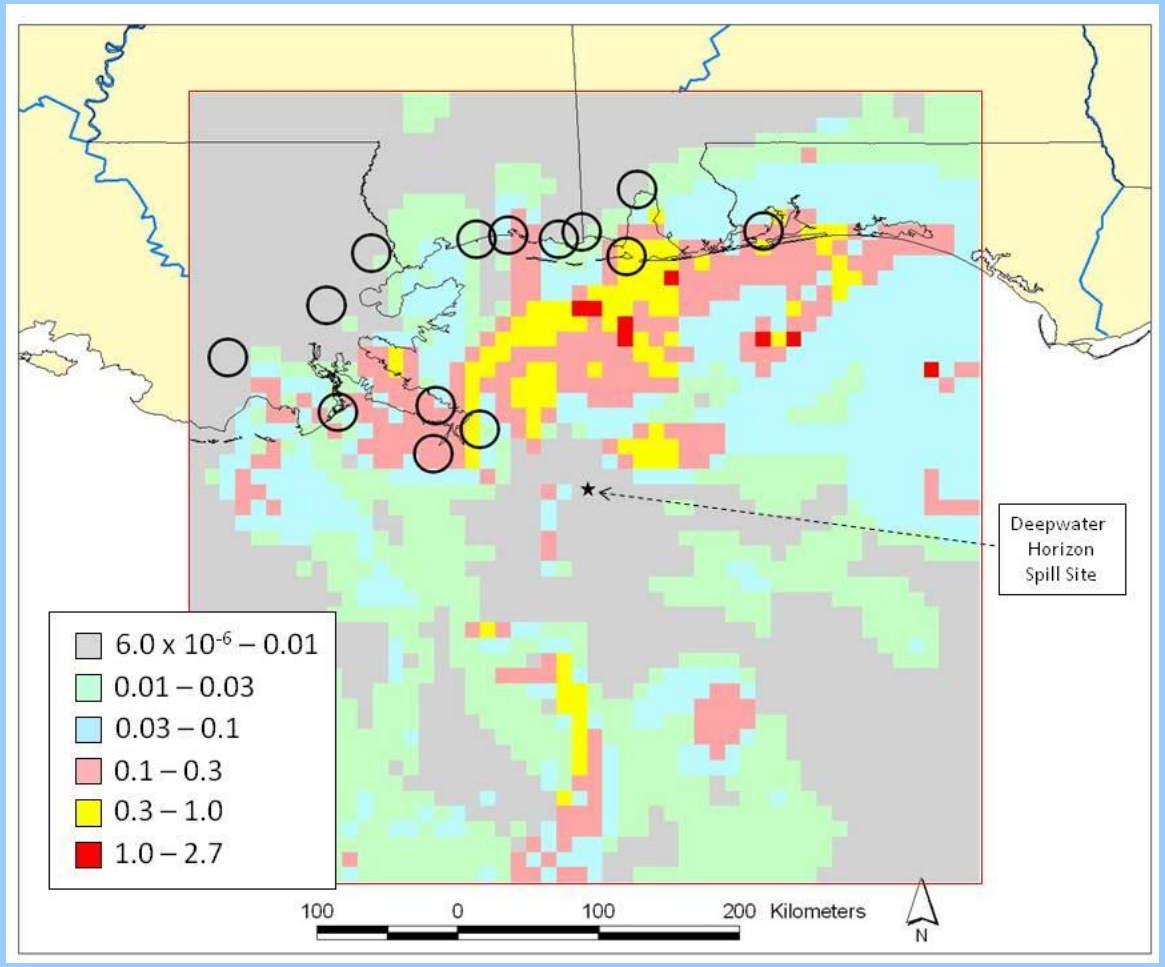

Figure S-5. Maximum modeled 24-hr average ground-level concentrations (fg TEQ/m3) for each grid square over the entire modeling period April 28 – July 22, 2010.

- Grid cells were divided into categories based on the distance between their centroid and the spill site: 0-25 km, 25-50 km, 50-75 km, … up to largest range of 225-250 km.
- This figure shows that the average modeled concentration [averaged over all directions] was largest in the distance range 100-125 km from the spill site.

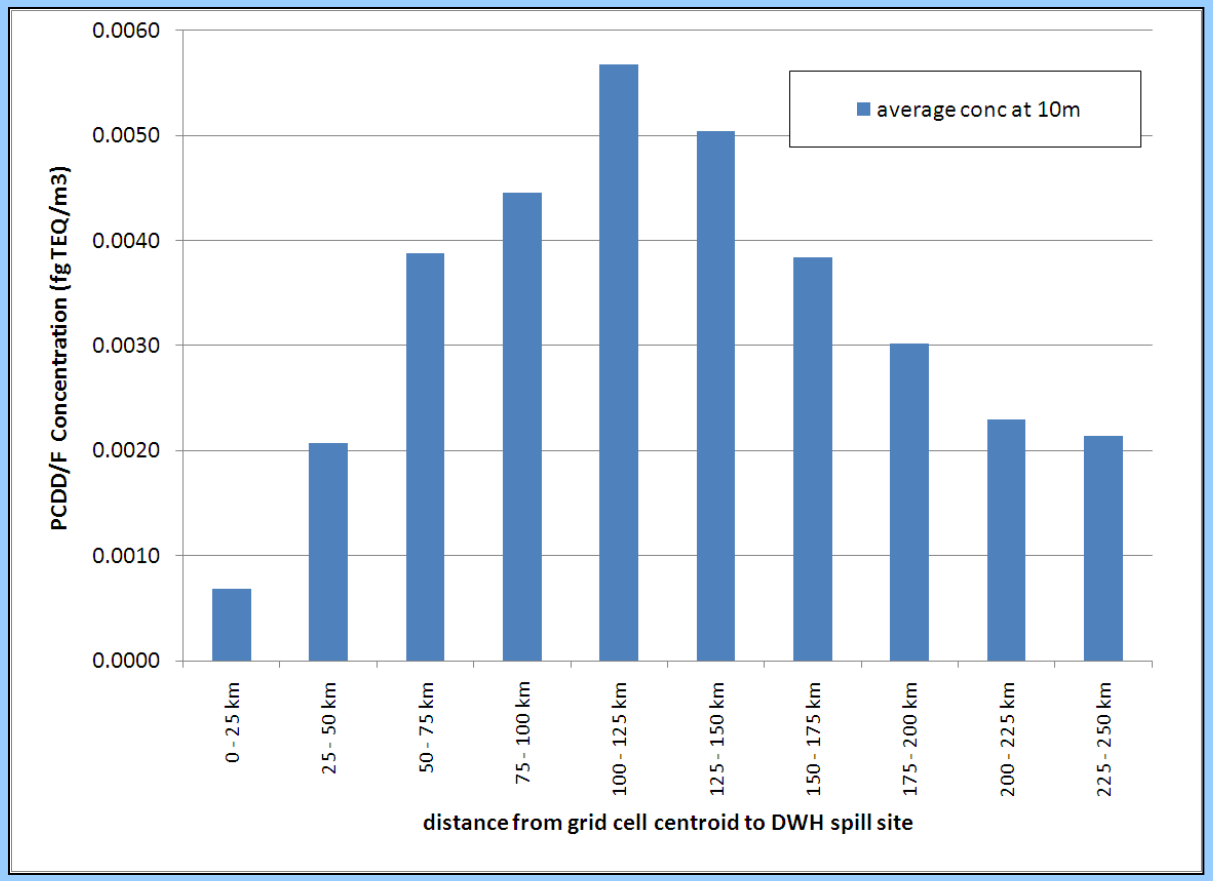

Figure S-6. Average concentration as a function of distance range from the DWH spill site for grid squares, over the entire modeling period April 28 – July 22, 2010.

- This figure shows that the distance ranges with the highest single grid-square average concentrations are 125-150 km, 150-175 km, and 225-250 km.
- This figure just represents the values of the grid cell in a given distance range that has the highest average concentration over the modeling period.
- Note that the highest, modeled grid-cell overall average 10m concentration was 0.051 fg TEQ/m3, and this occurred at a grid cell approximately 125 km northeast from the spill site.

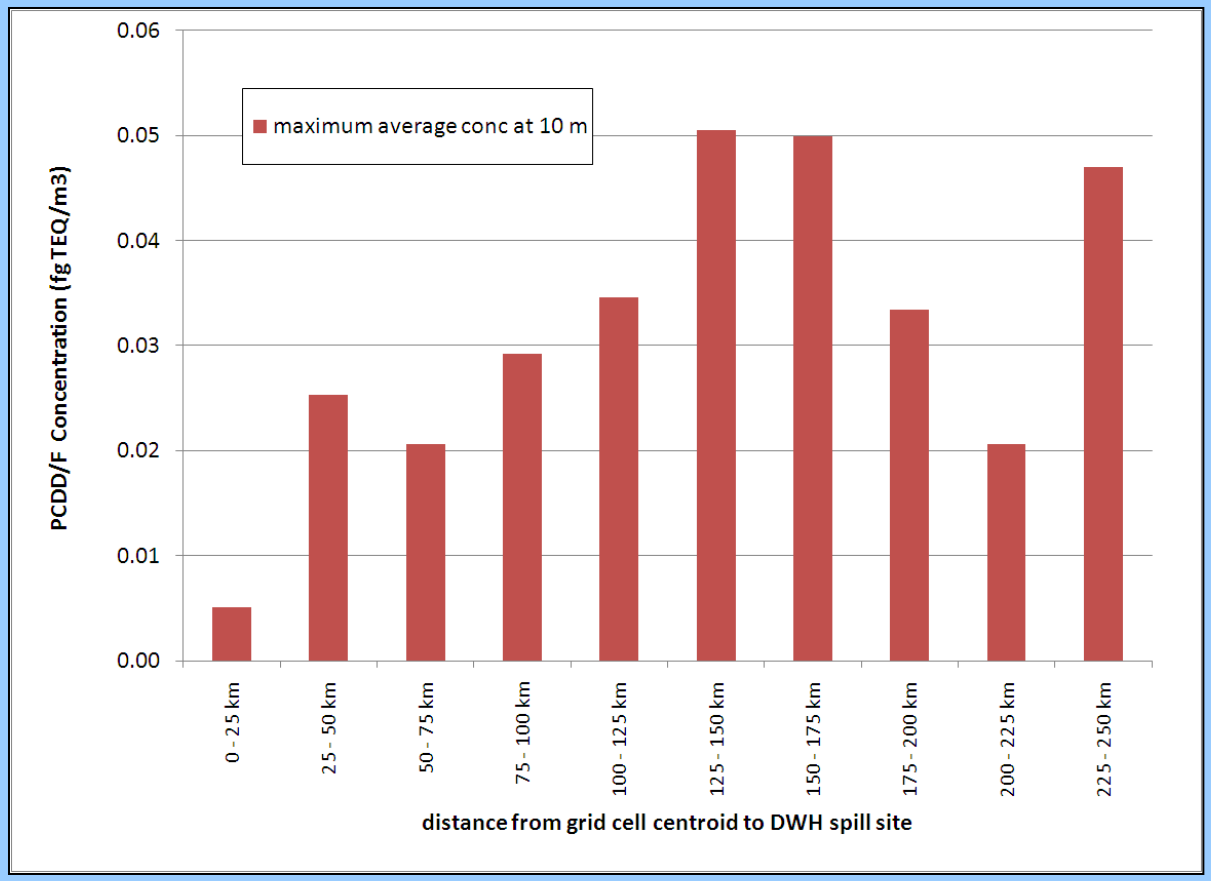

Figure S-7. Maximum grid-square average concentration as a function of distance range from the DWH spill site, over the entire modeling period April 28 – July 22, 2010.

- This figure shows the total modeled PCDD/F deposition (ug TEQ) in different distance ranges away from the spill site.
- While the flux decreases significantly at large distances from the site, the area over which this flux occurs increases.
- Thus, Figure S-9 shows that the while the total deposition maximum also occurs in the distance range 50-75 km away from the spill site, the deposition amounts do not drop off as significantly at further distances.

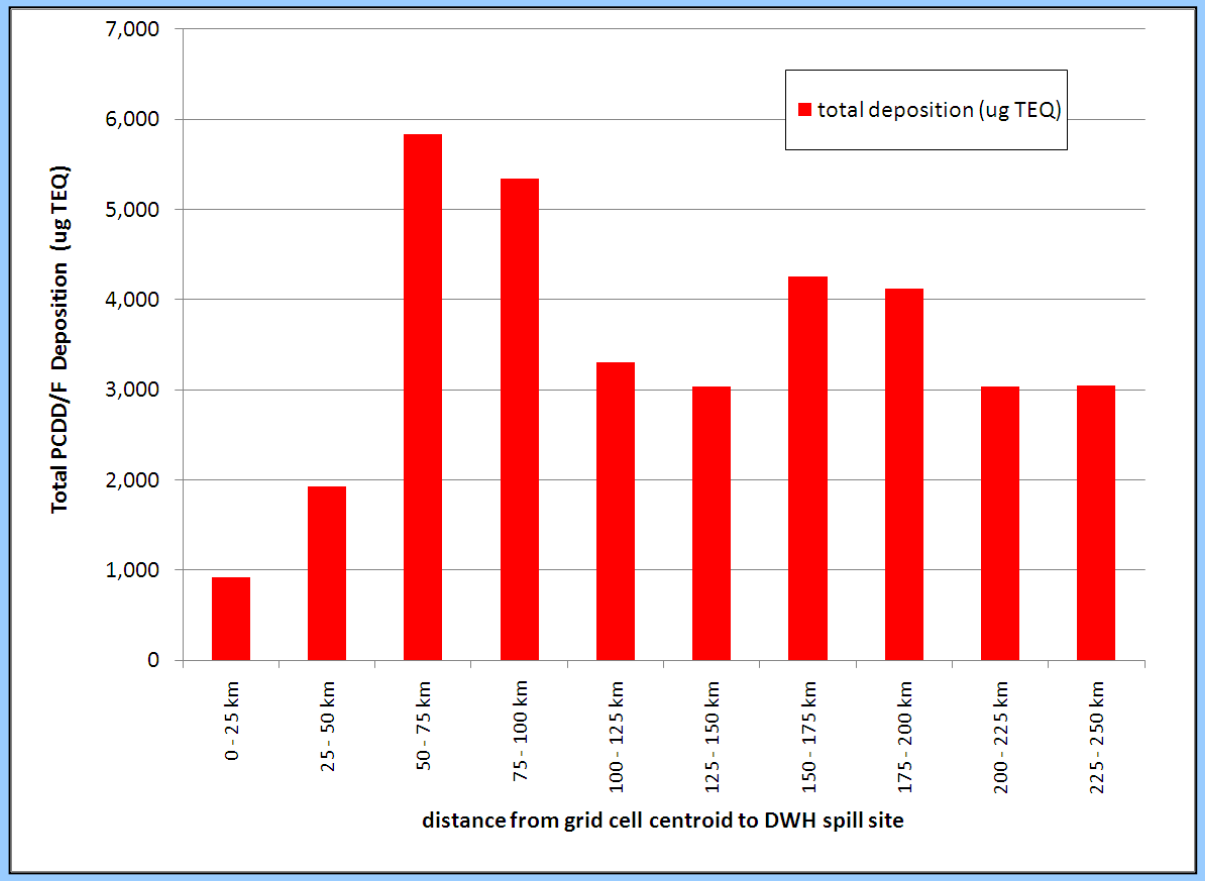

Figure S-9. Total PCDD/F deposition flux (ug TEQ) in different distance ranges from the DWH spill site, over the entire modeling period April 28 – July 22, 2010.

- This figure shows the same data as Figure S-9, above, except that the deposition totals have been normalized by the total estimated emissions from the oil burning activities (0.134 g TEQ).
- It can be seen that approximately 4% of the total emissions were deposited in the range 50-75 km away from the spill site.
- Approximately 26% of the emissions (on a TEQ basis) were deposited with 250 km of the spill site.

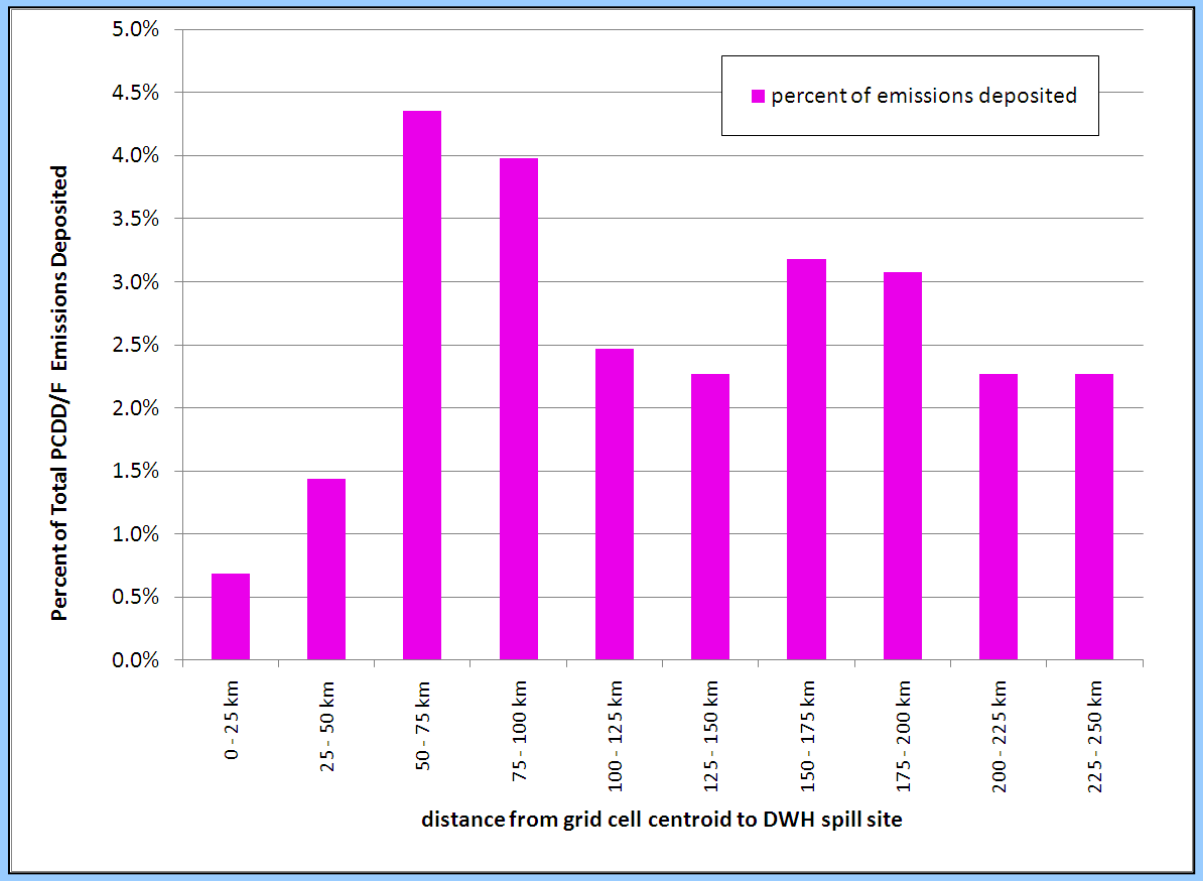

Figure S-10. Percent of total PCDD/F emissions from oil burning deposited in different distance ranges from the DWH spill site, over the entire modeling period April 28 – July 22, 2010.

- The HYSPLIT modeling was carried out over the domain shown in this figure.
- The domain extends approximately 5 degrees in each direction from the DWH spill site.
- A deposition mass balance analysis was performed for each of the seventeen 2,3,7,8-substituted congeners simulated with the HYSPLIT-SV model over this entire modeling domain, and the results are shown in the following slides.
- Note that all other modeling results presented here were tabulated and displayed on a smaller, finer grid, extending 2.5 degrees in each direction from the DWH spill site (shown in slide #4).

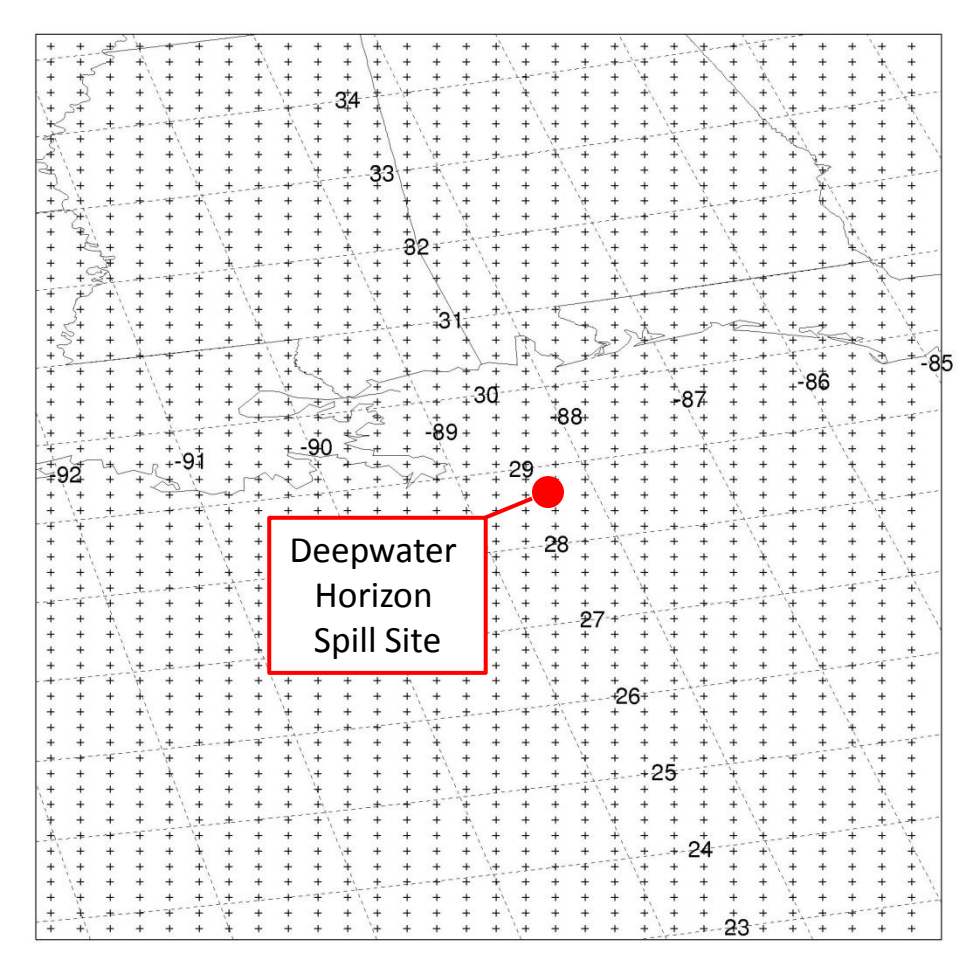

Figure S-11. Overall HYSPLIT-SV modeling domain on which the mass balance results of this section are based.

- This figure shows the fraction of total modeled deposition over the entire modeling domain accounted for by dry deposition, for both the vapor and the particle phases.
- For each congener, wet deposition accounted for the remaining fraction of total deposition.
- For example, for 2,3,7,8-TCDD, approx. 30% of the deposited mass was dry deposited in the vapor phase, about 2% was dry deposited in the particle phase, and the remaining 68% was wet deposited.
- The relative importance of different deposition pathways appears to be consistent with the expected vapor/particle partitioning behavior of the different congeners.

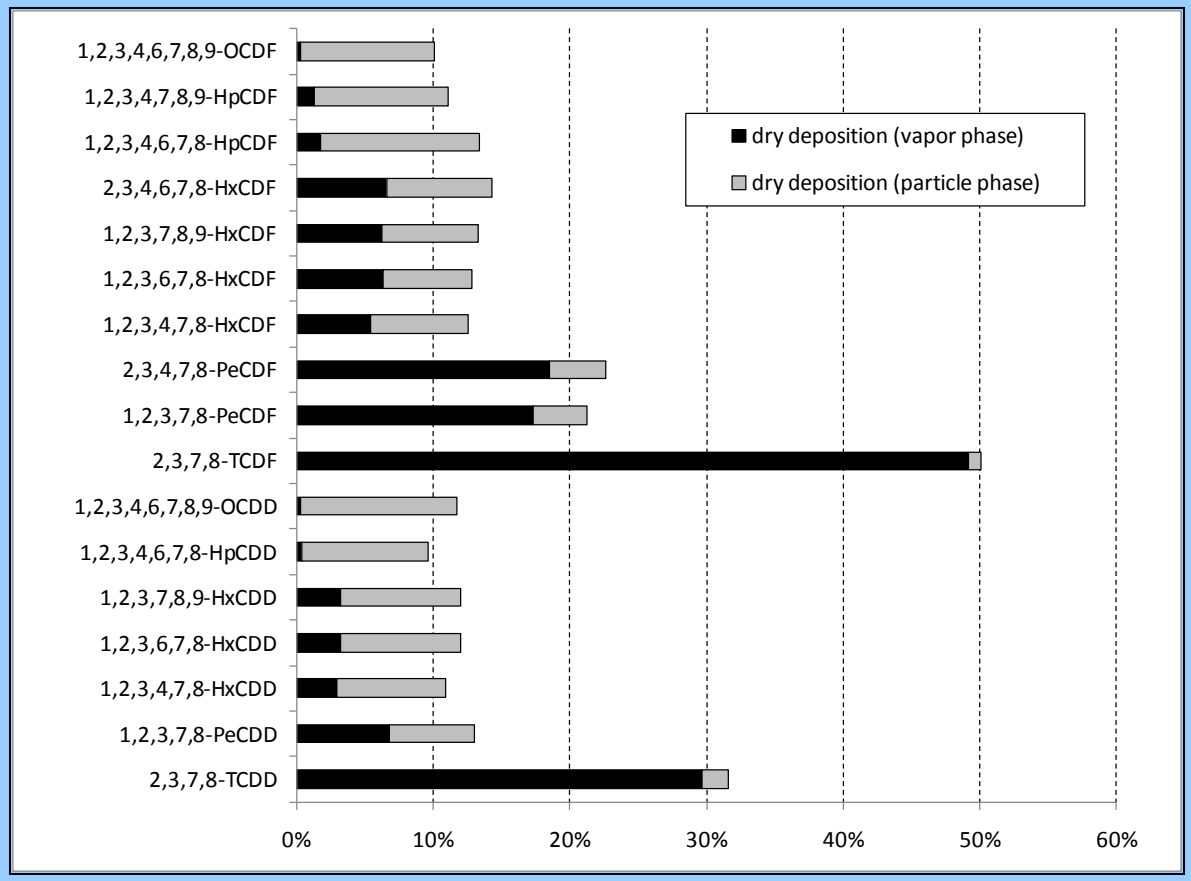

Figure S-12. Percent of total modeled deposition for a given congener over the modeling domain simulated to be dry deposited. For each congener, the remaining deposition was through wet deposition processes.

- In this figure, the total deposition (on a TEQ basis) over the entire modeling domain is presented for each modeled congener.
- Note that since the TEQ emissions factor for OCDD was zero, the modeled TEQ deposition for this congener is also zero.
- It can be seen that the most important congeners contributing to deposition (on a TEQ basis) over the entire domain were 1,2,3,7,8-PeCDD and 2,3,4,7,8-PeCDF.
- Wet deposition was the most important deposition pathway for each of these two congeners.

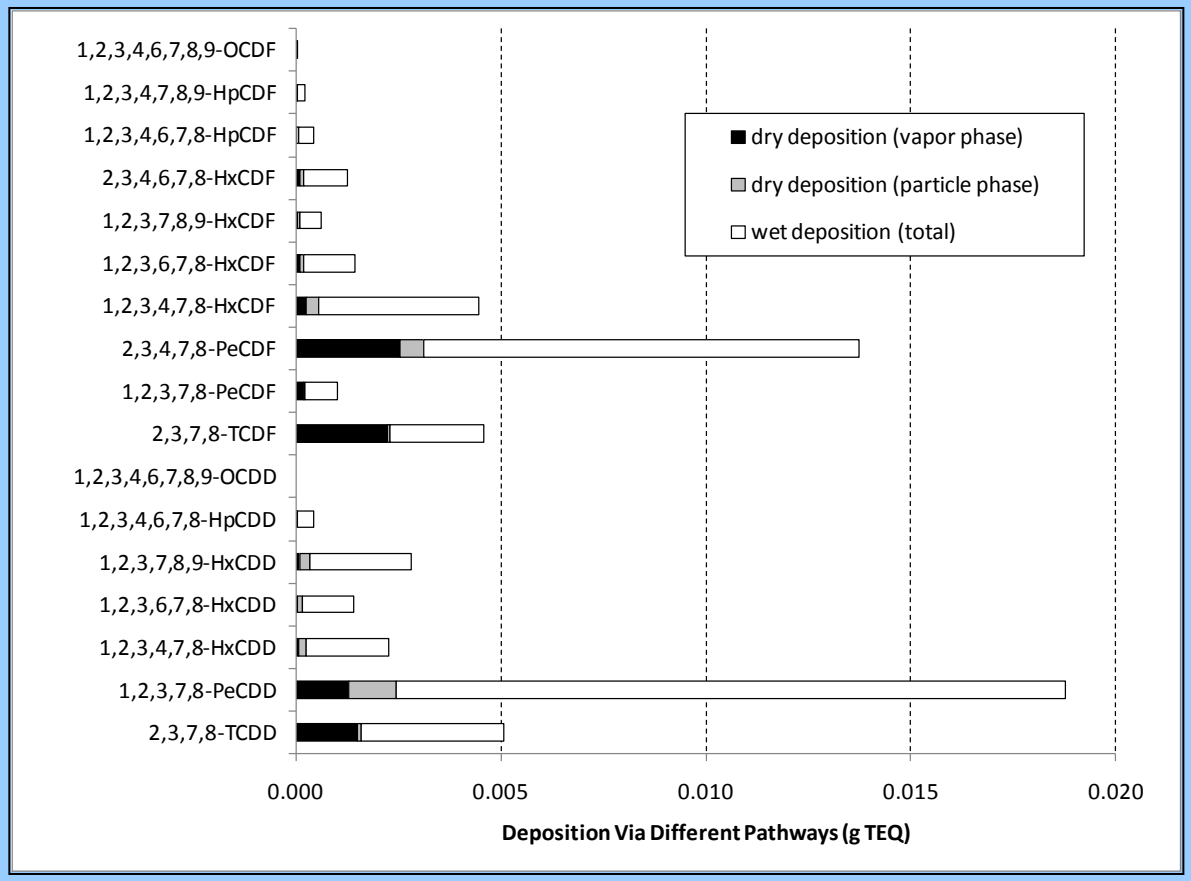

Figure S-13. Total deposition of each congener over the entire modeling domain, using the model inputs as described in the main paper, e.g., upper end of range of amount of oil burned and assuming congeners not detected during the emissions testing were present at their detection limit.

- In this figure, the fraction of the total emissions deposited over the entire modeling domain is shown for each congener.
- It can be seen that approximately 40% of the total emissions were deposited in the modeling domain for each congener.

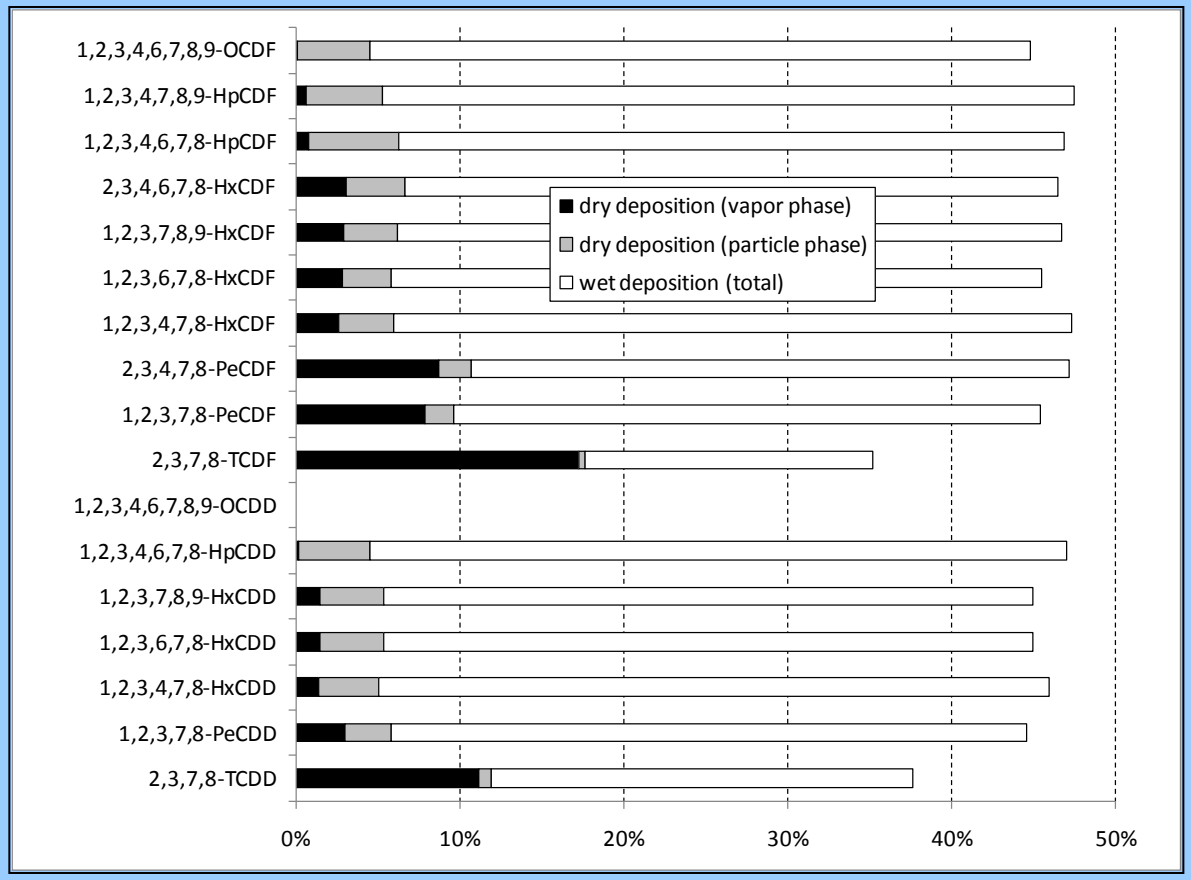

Figure S-14. Fraction of the total emissions of each congener deposited over the entire modeling domain.